ʾRODUCTION OF SOLID FUEL FROM TORREFACTION: EFFECT OF TEMPERATURE AND PROCESS TIME

by

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ABSTRACT

The purpose of this study is to investigate the torrefaction of palm oil trunks and fronds in packed bed reactor. Different temperature and process time were considered. The difference in temperature during torrefaction has great influence on the mass yield and energy yield of the torrefied palm oil trunks and fronds. Three different temperatures of 220, 250, and 300°C are used. The process times are 30, 60, and 90 minute.

The increase in temperature result in lower mass yield but increase in energy yield. Also, an increase in the weight loss, calorific value, percentage of carbon element, and decrease in percentage of oxygen element observed [1].Theoretically, the mass yield will be decreased as the temperature increase. Since batch wise packed bed reactor is used in this study, the process time will refer to time elapsed in batch-wise operation.

CHAPTER 1: INTRODUCTION

1.1 Background of the Project

According to statistics provided by the International Energy Agency in 2003, renewable accounted for 13.3% of the Total Primary Energy Supply (TPES). Biomass contributes the bulk (97%) of all combustible renewable and waste energy [2].In Malaysia alone, there are total of 2.65 million hectares oil palm cultivation. Only 10% used as oil. The remainder consists of huge amount of lignocellulosic materials such as oil palm fronds, trunks and empty fruit bunches. The figures are as follow [3]:

- 7.0 million tons of oil palm trunks
- 26.2 million tons of oil palm fronds
- 23% of Empty Fruit Bunch (EFB) per ton of Fresh Fruit Bunch (FFB) processed in oil palm mill

Looking at this enormous potential, this paper aims to shed some light by the study of palm oil waste using torrefaction process. There is also some paper reported about the reliability and the potential of biomass in Malaysia[4].

1.2 Problem statement

Several drawback of biomass must be overcome in order to be able to utilize the biomass waster efficiently [5] :

- Higher energy consumption for collection.
- Heterogeneous and uneven composition.
- Lower calorific value.
- Difficult to transport.

This project interested in the studies of torrefaction of oil palm trunk and fronds is using a packed bed reactor. More in depth interest will be the effect of torrefaction temperature and time on the mass and energy yields, and the properties of the torrefied biomass.

1.3 objective and scope of study

- To produce solid fuel from oil palm trunks and fronds by torrefaction process.
- The study the effect of temperature and process time on the mass and energy yields.
- To investigate the properties of the torrefied biomass.

CHAPTER 2: LITERATURE REVIEW

2.1 Biomass

2.1.1 Renewable Energy

Biomass can be understood as regenerative (renewable) organic material that can be used to produce energy. These sources include aquatic or terrestrial vegetation, residues from forestry or agriculture, animal waste and municipal waste. In other words, biomass is manufactured from crops, wood, manure, land fill gasses and alcohol fuels. Ethanol is a prime example of biomass alcohol fuel. Producing fuel and energy from biomass is a complex procedure but the principle behind it corresponds directly to photosynthesis. This is a chemical reaction in which carbon dioxide and water are transformed into oxygen gas and glucose through the input of energy from the sun. Plants become autotrophs because they use glucose as a source of energy rather than fossil fuels.

Biomass is one of the most plentiful and well-utilized sources of renewable energy in the world. [6]Broadly speaking, it is organic material produced by the photosynthesis of light. The chemical materials (organic compounds of carbons) are stored and can then be used to generate energy. The most common biomass used for energy is wood from trees. Wood has been used by humans for producing energy for heating and cooking for a very long time.

Biomass has been converted by partial-pyrolysis to charcoal for thousands of years. Charcoal, in turn has been used for forging metals and for light industry for millennia. Both wood and charcoal formed part of the backbone of the early Industrial Revolution (much northern England, Scotland and Ireland were deforested to produce charcoal) prior to the discovery of coal for energy.

2.1.2 Lignocellulosic Biomass

The main constituents contained in biomass include hemi cellulose, cellulose and lignin [7]. These three polymeric structures are mainly considered in most of the studies to understand the decomposition mechanisms of woody and herbaceous biomass. They form the foundation of cell walls and provide mechanical strength and tenacity (toughness) to plant structures. Below is basic structure in leaf and the position of hemicelluloses, cellulose, and lignin.

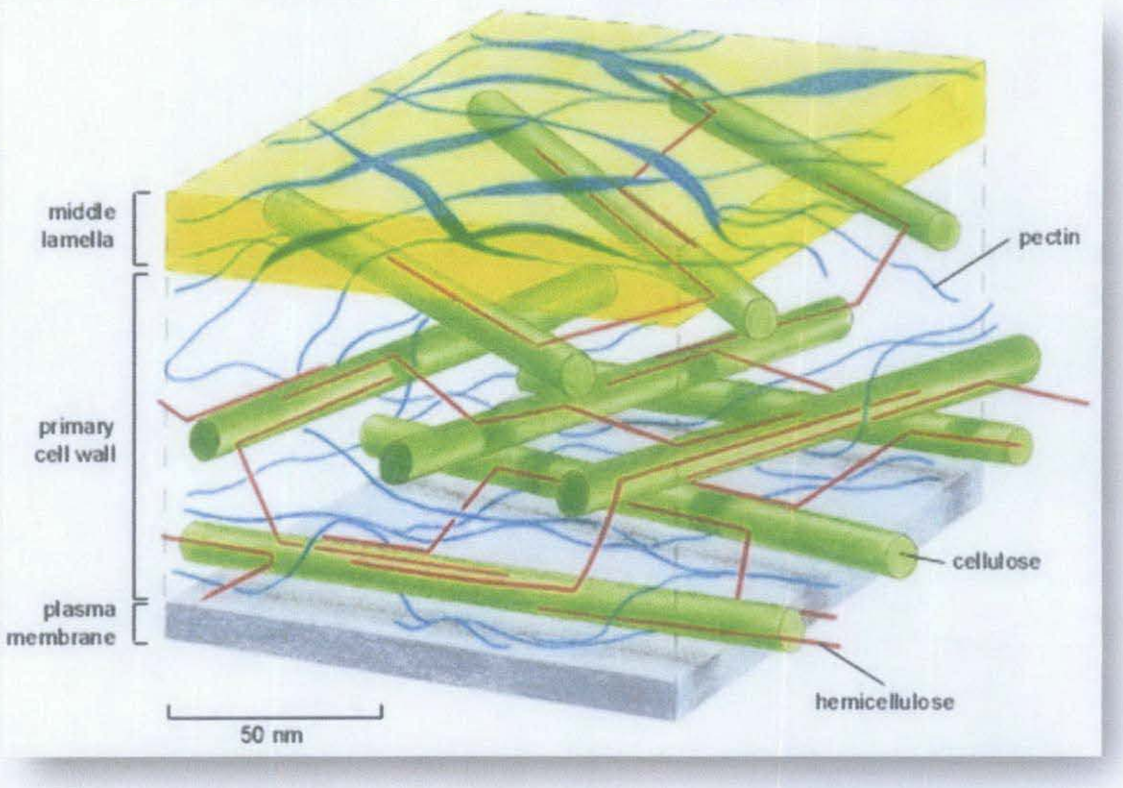

Figure 1 : Basic Structure in leaf [8]

2.1.3 Decomposition Mechanism during torrefaction

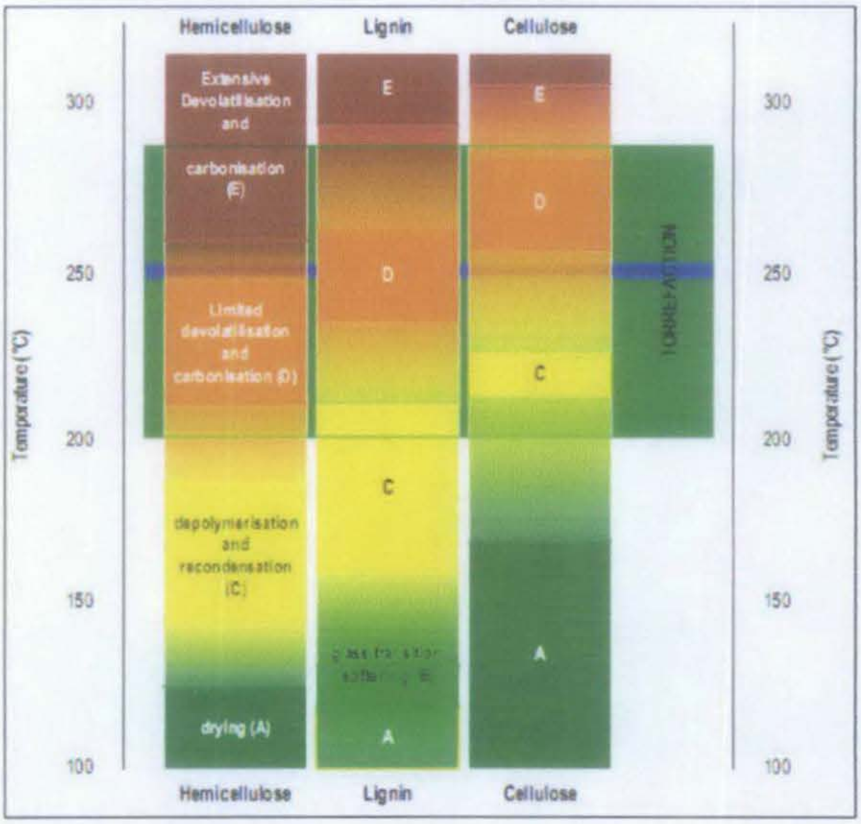

Figure 2: Decomposition regime in lignocelluloses during torrefaction

Based on the figure taken from [2], in temperature regime A, physical drying of biomass occurs. When the temperature is increased to regime C, depolymerisation occurs and the shortened polymers condense within the solid structure. In regime D, limited devolatilisation and carbonization of the intact polymers and the solid structures formed in the temperature regimes C. Further increase of temperature to regime E leads to extensive devolatilisation and carbonization of the polymers and the solid products that were formed in regime D. For lignin, it undergoes a temperature regime B which softening of it occurs.

2.2 Properties of Biomass

Pongsak Hengniran has discussed the RPR (Ratio Product Ratio) and calorific values of agricultural residues in his report. Table 1 show the result of his report.

Demirbas. A, (2002) has discussed the difference between fuel properties of biomass and coal. The fuel density of coal is 61% higher than biomass which is very significant.

Meanwhile, the particle size of coal is much finer than biomass. This parameter may also influence the heating value. Nevertheless, author does not find any report specifically discussed the effect of particle size on fuel properties. In Table 2, it shows that carbon content of coal is the highest among red oak wood and wheat straw. This support the fact that coal has higher dry heating value than biomass because the dry heating value is largely contributed by fixed carbon content.

Table 1: RPR and calorific values of agricultural residues [9]

Product	Residue	Moisture (%)	RPR	LHV (MJ/kg) (as received)
Sugarcane	Bagasse	50.00	0.250	6.43
	Top & trash	50.00	0.302	6.82
Paddy Rice	Husk	8.83	0.230	12.85
	Straw (top)	8.17	0.447	8.83
Oil palm	Empty bunches	8.81	0.428	16.44
	Fiber	10.11	0.147	16.19
	Shell	13.00	0.049	17.00
	Frond	48.34	2.604	7.97
	Male bunches	13.82	0.233	14.86
Cassava	Stalk	-	0.088	16.99
	Rhizome			
	Leave			
Maize	Corn cob	8.65	0.250	16.63
	Stalk			
Cotton	Stalk	9.33	3.232	13.07
Soybean	Stalk, Leaves, Shell	-	2.663	18.00

Table 2: Physical Properties and heating Values of Biomass and Coal Fuels [10]

Property	Biomass	Coal
Fuel density (kg/m^3)	~500	~1300
Particle size	~3 mm	~100
Dry heating value (MJ/kg)	16	25

Table 3: Ultimate Analyses of Typical fuel Samples [10]

	C	H	N	S	Cl	Ash	O (d
Coal	81.5	4.0	1.2	3.0	–	7.0	3.3
Red oak wood	50.0	6.0	0.3	–	–	1.3	42.4
Wheat straw	41.8	5.5	0.7	–	1.5	15.0	35.5

2.3 Torrefaction

2.3.1 Research Work

Many research works were being carried out related to torrefaction. There are reports found regarding the effects of torrefaction on fuel qualities and combustion [11], torrefaction of wood, weight loss kinetics and grindability [12][13][14], and also techno – economic evaluation [15]. The common parameters that are evaluated for the terrified biomass are calorific value and ultimate analysis [11][16][17][18]. Biomasses that have been studied included willow, beech, larch, straw, reed canary grass birch, pine and bagasse [19][11][18]. The author found no paper discussed the torrefaction of palm oil waste.

2.3.2 Temperature and process time

High moisture content is one of the drawbacks in biomass fuel. Torrefaction is a method used to improve the properties of biomass fuel under certain condition. Packed bed reactor is used in this experimental procedure by slow heating of biomass in an inert atmosphere to a maximum temperature of 300 °C. The end product yields a solid uniform product with lower moisture content and higher energy content compared to those in the initial biomass. [4]

Temperature difference and process time have great influence on the mass yield and energy yield of the torrefied biomass. Based on the literature review, the mass yield in *inversely proportional with temperature* [11] [1].

Process time is defined as the time elapsed in the packed bed reactor. Previous study shown that operation is favored at certain process time to intensify the heating value and grindability as well as to avoid too much loss of the biomass. [1]

2.4 Torrefied biomass

There are numbers of methods to optimize the efficiencies of solid fuels. However, torrefaction will be the main interest in this experiment. It is important to identify the properties of the torrefied biomass to have the insight of the experiment. It has the following properties [3]:

- Hydrophobic nature: the material does not regain humidity in storage and therefore unlike wood and charcoal, it is stable and with well-defined composition.
- Lower moisture content and higher calorific values compared to biomass
- Formation of less smoke when burnt.
- Higher density and similar mechanical strength compared to the initial biomass
- Desired form
- Suitable for various applications as a fuel - in the steel industry, combustion and gasification.

2.4.1 Mass Yield

The mass and energy yield are main parameters in the evaluation of the torrefaction process. Based on [4], mass and energy yield can be defined as equation (1) and (2). Respectively

$$Y_{mass} = 100\% \times \left(\frac{mass\ after\ drying\ or\ torrefaction}{mass\ of\ wet\ sample\ before\ the\ treatment}\right) \qquad (1)$$

$$Y_{energy} = Y_{mass} \times \left(\frac{LHV\ after\ treatment}{LHV\ before\ treatment}\right) \qquad (2)$$

2.4.2 Ultimate analysis, calorific value and moisture content

Table 4: Heating value and elemental analysis [1]

Torrefaction temperature (°C)	Torrefaction time (h)	Higher heating value, HHV (MJ/kg, db[a])	Elemental analysis (wt%, daf[a])			
			C	H	O	N
Raw wood	–	20.70	48.77	6.77	44.36	0.10
220	0.5	23.20	54.33	6.99	38.53	0.15
	1	23.23	54.91	6.85	38.07	0.17
	1.5	23.69	55.15	6.65	38.12	0.08
	2	23.77	55.65	6.25	37.97	0.13
250	0.5	26.92	64.40	6.37	29.11	0.12
	1	27.52	65.37	6.06	28.41	0.16
	1.5	27.77	65.60	5.92	28.35	0.13
	2	28.16	66.73	5.84	27.30	0.13
280	0.5	28.08	64.76	5.92	28.88	0.44
	1	28.38	65.76	5.47	28.61	0.16
	1.5	28.77	69.79	5.77	24.31	0.13
	2	28.93	70.25	5.35	24.23	0.17

[a] Dry ash free basis.

Table 5: Ultimate analysis, HHV, and moisture content of treated and untreated biomass [11]

	Raw	Torrefaction temperature (K)			
		503	523	543	563
RCG					
C (%)	48.6	49.3	50.3	52.2	54.3
H (%)	6.8	6.5	6.3	6.0	6.1
N (%)	0.3	0.1	0.0	0.1	0.1
O (%)	37.3		37.0	37.3	36.3
Moisture (%)	4.7	2.5	1.9	1.3	1.2
CV (kJ/kg)	19,500	–	20,000	20,800	21,800
Wheat straw					
C (%)	47.3	48.7	49.6	51.9	56.4
H (%)	6.8	6.3	6.1	5.9	5.6
N (%)	0.8	0.7	0.9	0.8	1.0
O (%)	37.7		35.6	33.2	27.6
Moisture (%)	4.1	1.5	0.9	0.3	0.8
CV (kJ/kg)	18,900	19,400	19,800	20,700	22,600
Willow					
C (%)	49.9	50.7	51.7	53.4	54.7
H (%)	6.5	6.2	6.1	6.1	6.0
N (%)	0.2	0.2	0.2	0.2	0.1
O (%)	39.9	39.5	38.7	37.2	36.4
Moisture (%)	2.8	0.5	0.1	0.1	0.0
CV (kJ/kg)	20,000	20,200	20,600	21,400	21,900

Based on the above figure retrieved from [1], heavier heating value (HHV) of Lauan wood increase. Calorific Value of Root Canary grass, Wheat straw and Willow increases when the torrefaction temperature increases[11]. Moisture content also observed to be decreasing with increasing temperature. Other than that, the carbon fixed content of the biomass also increases with the torrefaction temperature. Prins et al (2006)relate both fixed carbon content and calorific value are by equation (3). From the equation, the value of coefficient **a, b, c,** and **d** are decreasing respectively. Therefore, as a is the coefficient for fixed carbon content, **C**, the value of **C** give the greatest influence to calorific value.

$$HHV\ [MJ/kg]=a*C+b*H+c*O+d \qquad (3)$$

Meanwhile, the moisture content is decreased when the torrefaction temperature increase.

2.4.3 Ash content

Ash, the material remaining, calculated on the basis of the dry weight of the original sample, after the sample is ignited at a specified temperature. The ash content of the sample may consist of: (1) various residues from chemicals used in its manufacture, (2) metallic matter from piping and machinery, (3) mineral matter in the pulp from which the paper was made, and (4) filling, coating, pigmenting and/or other added materials. The amount and composition of the ash is a function of the presence or absence of any of these materials or others singly or in combination [20]. Torrefaction also increase the ash content of the fuel. Biomass torrefied at higher temperature results in higher in ash content [4][21]. Up to date, there is no specific explanation found to justified this statement. Ash is a solid, particulate, inorganic combustion residue. Of forest fuels, ash content varies between different components, stem wood 0, 4-0, and 6%, and stem bark 2-5% and 1-2% branches. The ash content is highest in those parts of the tree where growth occurs. Ash from the wood fuel contains nutrients which the tree raised, including important trace elements. Nitrogen (N) is missing because it largely leaves in gaseous combustion. Since trees take up heavy metals and radioactive substances from soil and air, are also those substances in the ash. Generally, the ash is between 10% and 30% of calcium (Ca). The content of potassium (K) and magnesium (Mg) is usually a few percent, while the phosphorus (P) represents approximately one percent of the total content [22].

CHAPTER 3: METHODOLOGY

3.0 Process flow

The process flow of this project is shown as follow:

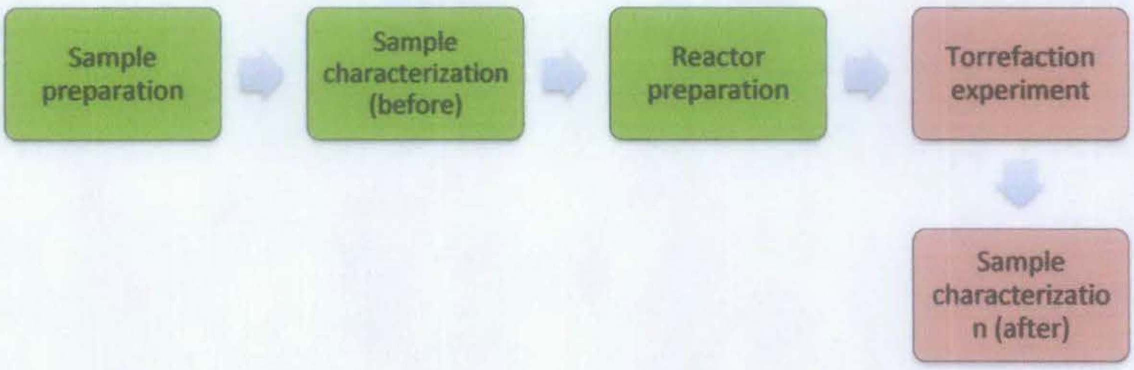

Figure 3: Process Flow

3.1 Sample Preparation

The biomass, palm oil trunks and fronds are obtained from FELCRA Nasaruddin in Bota, Perak.The leaves from the fronds is cut from the main stem and cut into smaller pieces about 2cm each. The stem also is also cut into smaller pieces about 3cm each. Then, this biomass is placed into one tray each. The chunks of trunk are cut into smaller pieces about 4 x 4cm each. It is then placed into iron trays .All three trays are then placed into the oven at temperature of 105^0C for 24 hours. The dried biomass was grinded and sieved to four size range 0.25-0.5mm.

3.1.1 Chemicals

Table 6: List of chemical used

Chemicals	Purity	Supplier's Name
Purified Nitrogen Gas	99.98%	MOX – Linde Sdn. Bhd.
Silica Gel	-	Bendosen

3.2 Characterization

Before and after the torrefaction process there five characterizations to be monitored:

No	characterizations	Measurement
1	Moisture content	A prescribed amount of sample (1g) was weighed in a petri dish, and was placed in an electric oven maintained at 105 °C. Reading is taken after hour 24, 24+1, 24+1+1 and 24+1+1+1.
2	Calorific value	It is measured using a bomb calorimeter, model C2000 series manufactured by IKA Werke. The calorific value from a bomb calorimeter is the high heat value (HHV), which includes the latent heat of the vapor emitted from the specimen.
3	Elementary (CHNS) analysis	It is carried out using CHNS-932 supplied by LECO Corporation. The carbon, hydrogen, nitrogen and sulfur contents were obtained from the analytical experiment. The oxygen content was calculated by the subtraction.
4	Ash content	A prescribed amount of sample (0.5 g) was weighed in a ceramic crucible, and was placed in an electric furnace. The temperature was raised to 700°C. After 3 h, the furnace was turned off and was allowed to cool down. The crucible containing the ash was weighed. The mass and energy yield will be calculate by following equation $y_M = \frac{\text{Mass of solid after torrefaction}}{\text{Mass of biomass used}} \quad (1)$ CV ratio $= \frac{\text{CV of solid after torrefaction}}{\text{CV of biomass used}} \quad (2)$

3.3 Reactor Preparation

The torrefaction process was carried out in a vertical tubular reactor with 100 mm internal diameter. The reactor was assembled by the writer as per following design:

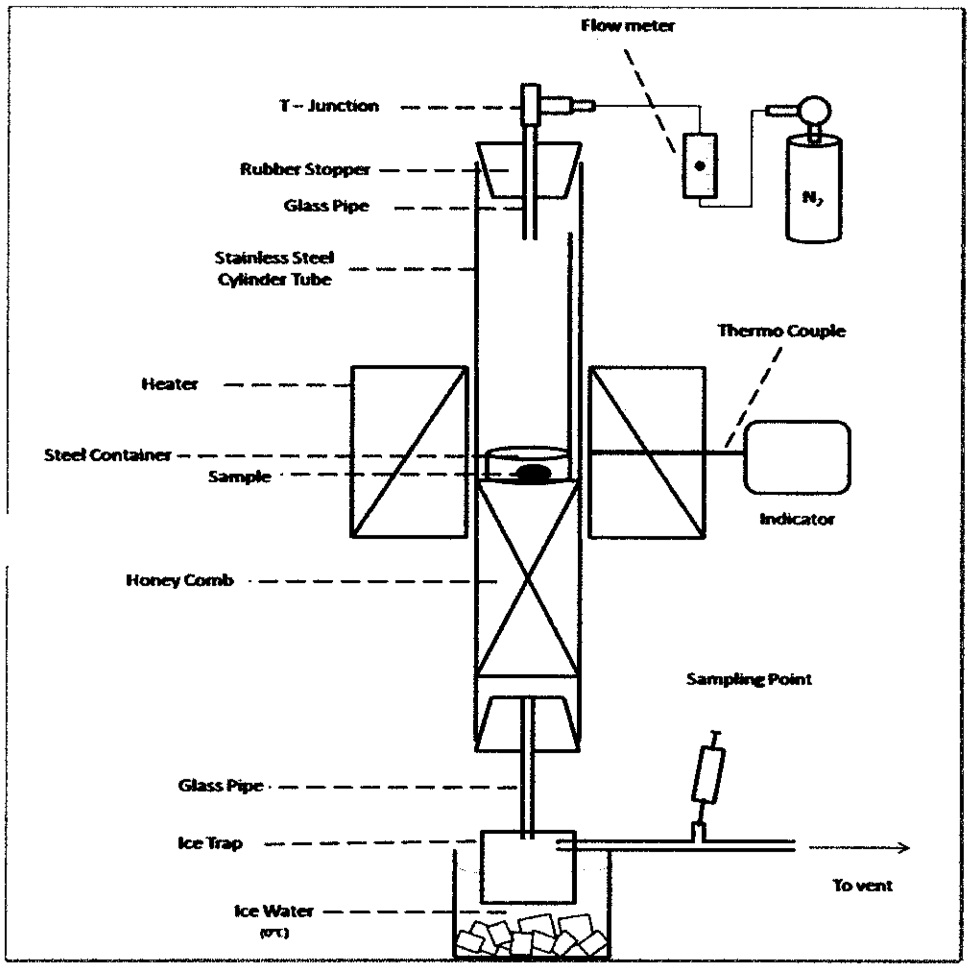

Figure 4 : Reactor diagram

3.4 Torrefaction Experiment

1. 3 gram of grinded sample of biomass is measured and carefully filled into the vertical reactor by using sample holder (metal wire hand-made holder).
2. The reactor is flushed with torrefaction gas for 15 minutes at N2 flow rate of 100ml/min.
3. After the flushing is completed, the N2 flow rate is set at 20ml/min and temperature is increased to the desired point (torrefaction temperature) by the rate of 10deg C/min by electric furnace surrounding the reactor.

4. The torrefaction temperature is maintained for 30 minutes. After 30 minutes, the temperature is set back to 10°C. The system temperature should be below 50°C before sample can be taken out.
5. The experiment will be repeated by varying three variables that are temperature, process time and particle size.

Table 7: parameter in the experiment

Variables	Variation Level
Temperature (^{0}C)	220 250 300
Process Time (min)	30 60 90

CHAPTER 4: RESULT AND DISCUSSION

The effect of process time is conducted at temperature of 300°C and three different process time; 30, 60, 90 min. The effect of temperature is conducted at process time of 60 min and three temperatures; 220, 250 and 300°C. However the effect of different temperature will not be discussed in this paper as the experiment is still ongoing.

4.1 Mass yield

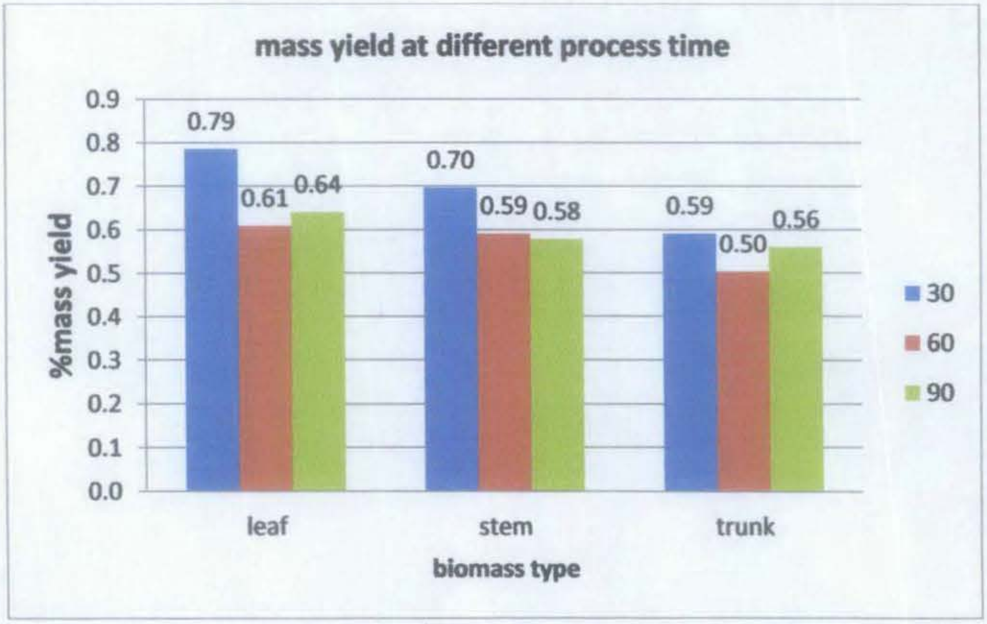

Figure 5: mass yield

Figure 5 show the mass yield of biomass for palm oil at different part; leaf, stem and trunk at different process time. It is observed that the highest mass yield is for leaf at process time of 30 min. This suggests that leaf contain the highest amount of hemicelluloses compare to the stem and trunk. It is also observed that the lowest mass yield is at different process time for each type of palm oil parts.

4.2 Ash content

Ash content analysis is carried out to indicate the nonvolatile inorganic matter of a compound which remains after subjecting it to a high decomposition temperature. The higher ash content in the biomass, the lower of the biomass is converted to energy.

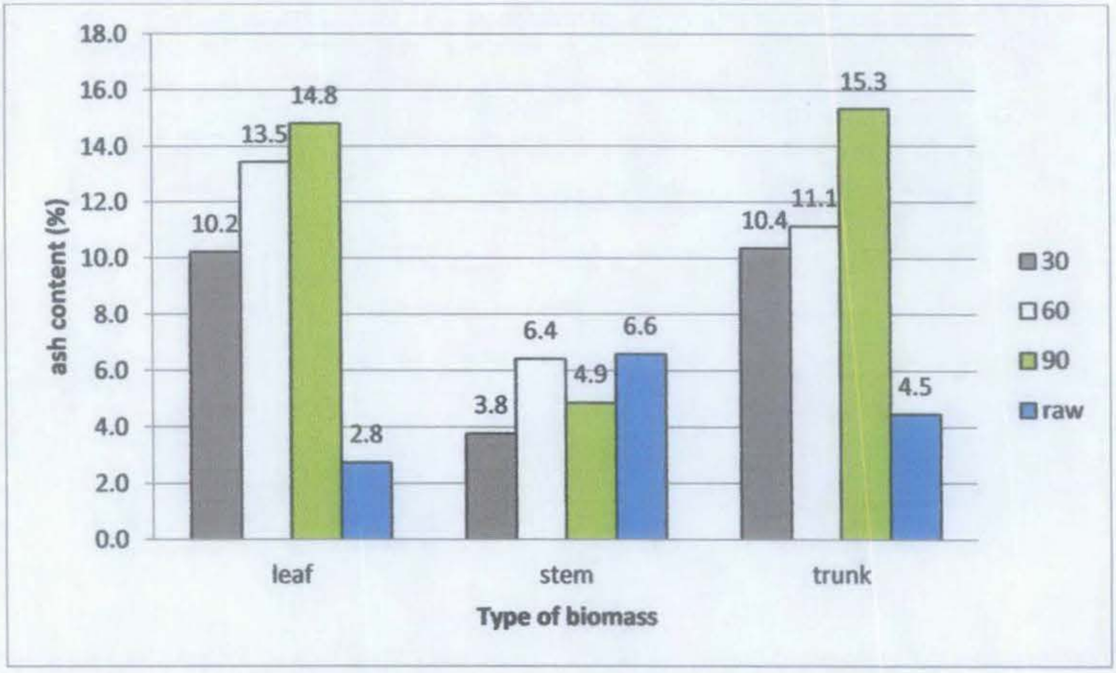

Figure 6: Ash Content

It can be seen from the graph above that the ash content increase as the process time is increase. Therefore 30 min is the suitable time to perform torrefaction on palm oil leaf, stem, and trunk as it has the lowest ash content. It is also seen that stem has the lowest ash content which point out stem as the best part among the three part in the context of ash content.

4.3 CV analysis

Calorific value is defined as the energy available in the biomass that is produced by complete combustion. The combustion process generates water vapor and certain techniques may be used to recover the quantity of heat contained in this water vapor by condensing it.

The Higher Calorific Value supposes that the water of combustion is entirely condensed and that the heat contained in the water vapor is recovered. The Lower Calorific Value supposes that the product of combustion contains the water vapor and that the heat in the water vapor is not recovered.

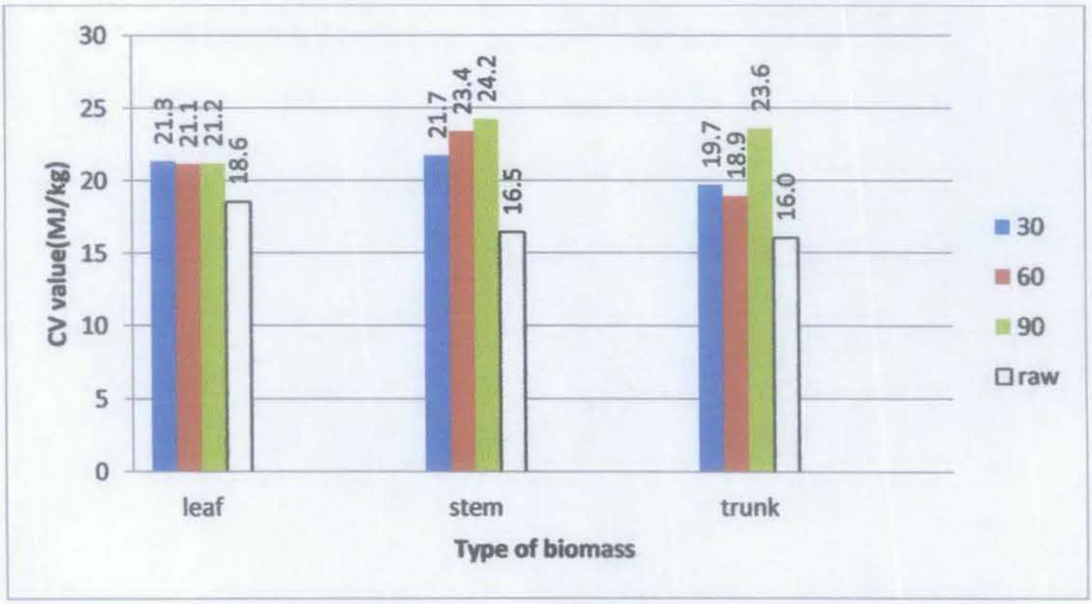

Figure 7: Calorific Value

There are significant increases in the value of calorific value of the biomass after torrefaction. The increase in each part is 13% for leaf, 32.1% for stem and 32.0% for trunk. It can be seen that stem torrefied for 60 min has the highest calorific value. This implies that stem has the highest calorific value. The result obtained also shows that the highest calorific value occur at process time of 60 min(green-colored bar),except for leaf despite the highest calorific value is observed in leaf before torrefaction (raw).This suggest that the best process time to yield high calorific value is at 60 min.

4.4 CHNS Analysis

CHNS analysis is conducted using CHNS-932 supplied by LECO Corporation. The result above shows the carbon contains in every part of the palm oil.

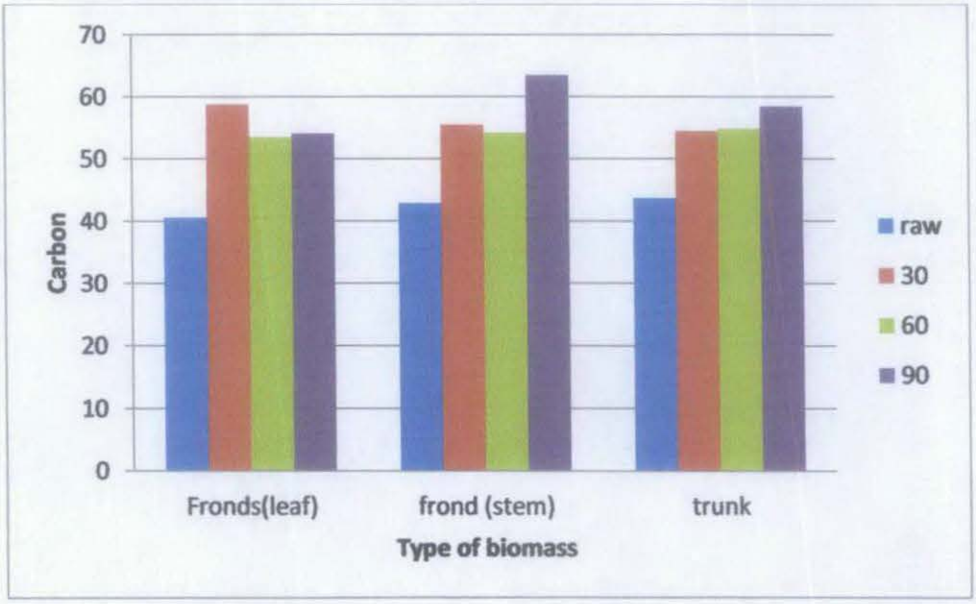

Figure 8: Carbon Content

All three parts show that the carbon content ranges almost the same. The highest carbon content is at 30 min for leaf and 90 min for both stem and trunk. Therefore the best process time to yield highest carbon is 30 min for leaf and 90 min for both stem and trunk.

4.5 Moisture Content Analysis

Water content or moisture content is the quantity of water contained in a material. Moisture content is the most important property with respect to the process energy efficiency. Only for very dry biomass feedstock lower efficiencies are to be expected.

Higher moisture content in the biomass is not good because it will slow down the residence time and there will not much biomass particle which will be torrefied.

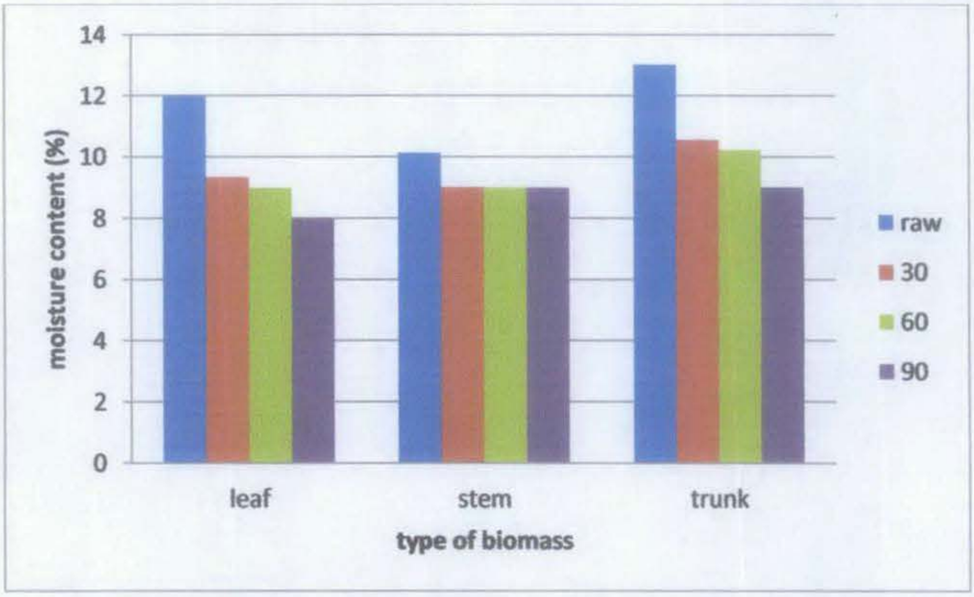

Figure 9: Moisture Content Analysis

Based on the graph, moisture content decrease noticeably as the process time increase. This is expected as more moisture evaporates in longer process time and thus implies that the longer the time, the more moisture will be driven out from the biomass.

4.6 Energy yield

Table 8 summarizes the result of torrefied palm oil trunk and fronds; leaf and stem. Energy yield varied with different process time. The energy yield is calculated by equation (2). It gives the information on the amount of energy that has been reserved after torrefaction [22]. From table 8 and figure 10, we can see that there are substantial energy increases after torrefaction. The highest increase is more obvious at 30 min for leaf and stem. However the case is different with trunk which the highest energy yield is observed at 90 min. This indicate that 30 min is the optimize time to carry torrefaction for palm oil leaf and stem while for trunk is 90 min.

Table 8: Ultimate Analysis

temperature (°C)	Process time (min)	Mass yield, yM (%)	CV ratio (%)	Calorific Value (MJ/kg)		Energy yield, yE (%)
				raw	torrefied	
300	30	78.57	114.18	18.67	21.32	89.71
	60	60.89	113.13		21.13	68.89
	90	64.07	113.43		21.18	72.68
300	30	69.63	131.88	16.46	21.71	91.83
	60	59.11	141.92		23.36	83.88
	90	57.85	147.12		24.22	85.11
300	30	59.11	122.43	16.09	19.70	72.37
	60	50.30	117.70		18.94	59.20
	90	55.96	146.66		23.59	82.07

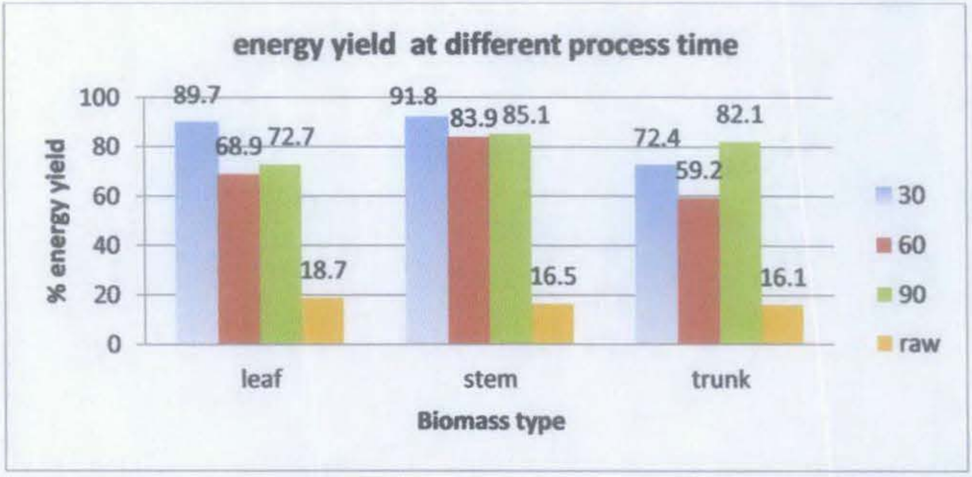

Figure 10: Energy Yield

The result of energy and mass yield are shown in Figure 10. For all product of torrefaction the energy yield and mass yield was greater than mass yield. The greatest difference between energy and mass yield occurred in stem at process time 90 min (32.03%). Leaf and trunk also showed a similar pattern for mass yield and energy differences. The greatest mass yield and energy yield different occurred at 90 min which are 32.02% for leaf and 31.88% for trunk.

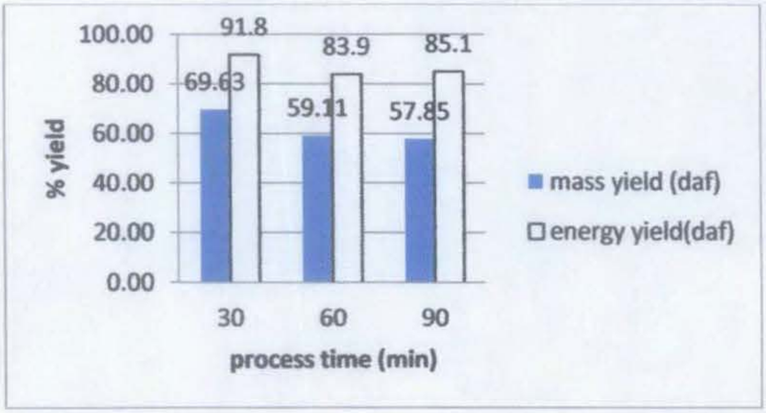

Figure 11: Mass and Energy Yield for frond (leaf)

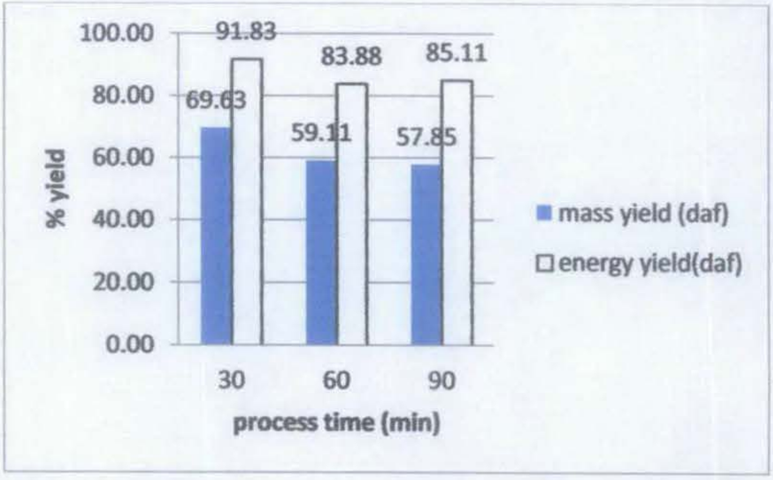

Figure 12: Mass and Energy Yield for frond (stem)

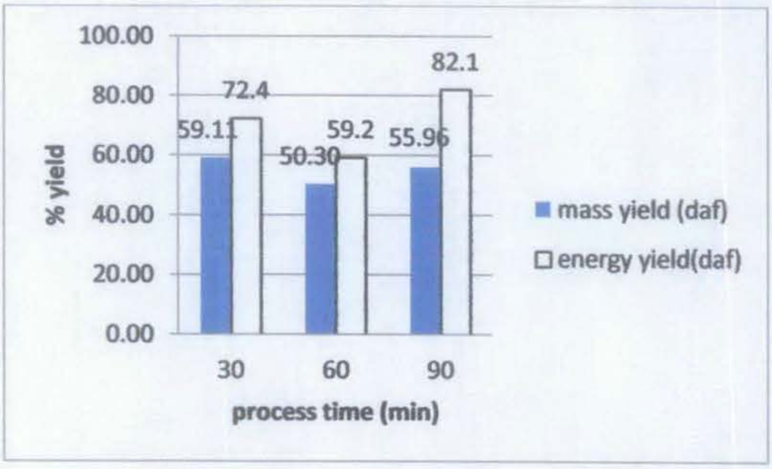

Figure 13: Mass and Energy Yield for frond (trunk)

CONCLUSION AND RECOMMENDATION

As conclusion frond (stem) is perceived to be the most suitable part of the palm oil to be used as biomass compare to frond (leaf) and trunk. This is due to the reason that it has averagely the highest mass yield, carbon content and energy yield but the lowest ash content and moisture content.

The effect of process time however varied. This statement can be is due to the fact that effect of temperature is more profound than the effect of process time [1]. However the observed effects for process time are as has been discussed before. The highest calorific value and carbon content is observed at 90 min, the highest mass yield, highest energy yield and lowest moisture content is however observed at 30 min.

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APPENDIX I

Result at temperature 300°

Biomass	Process Time (min)	m before (g)	m after (g)	Calorific Value (MJ/kg)	CV Ratio	Moisture Content (%)	Ash Content (%)	CHNS					Mass yield	Energy Yield
								Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen		
frond (leaf)	30	3.0054	2.3123	21.32150	114.1805	9.3328	10.2312	58.780	6.727	2.716	0.361	31.417	78.5705	89.712
	60	3.0012	2.0235	21.12600	113.1336	8.9846	13.4534	53.520	5.882	2.685	0.200	37.714	60.8948	68.892
	90	3.0125	1.828	21.18200	113.4335	8.0012	14.8271	54.065	4.924	2.838	0.267	37.906	64.0709	72.677
frond (stem)	30	3.0012	2.737	21.70800	131.8753	9.0056	3.7935	55.455	6.014	0.738	0.155	37.639	69.6323	91.827
	60	3.008	2.0673	23.36100	141.9173	9.0001	6.4270	54.160	4.580	0.727	0.149	40.385	59.1079	83.884
	90	3.0068	1.7371	24.21700	147.1174	8.9956	4.8836	63.455	4.413	0.793	0.115	31.225	57.8493	85.106
trunk	30	3.0027	2.453	19.69600	122.4343	10.5532	10.3682	54.505	4.179	1.712	0.405	39.200	59.1097	72.370
	60	3.0077	2.2597	18.93500	117.7037	10.2316	11.1465	54.890	4.008	1.176	0.338	39.589	50.2964	59.200
	90	3.0011	1.5104	23.59300	146.6588	9.0069	15.3453	58.480	4.990	1.233	0.602	34.696	55.9592	82.069

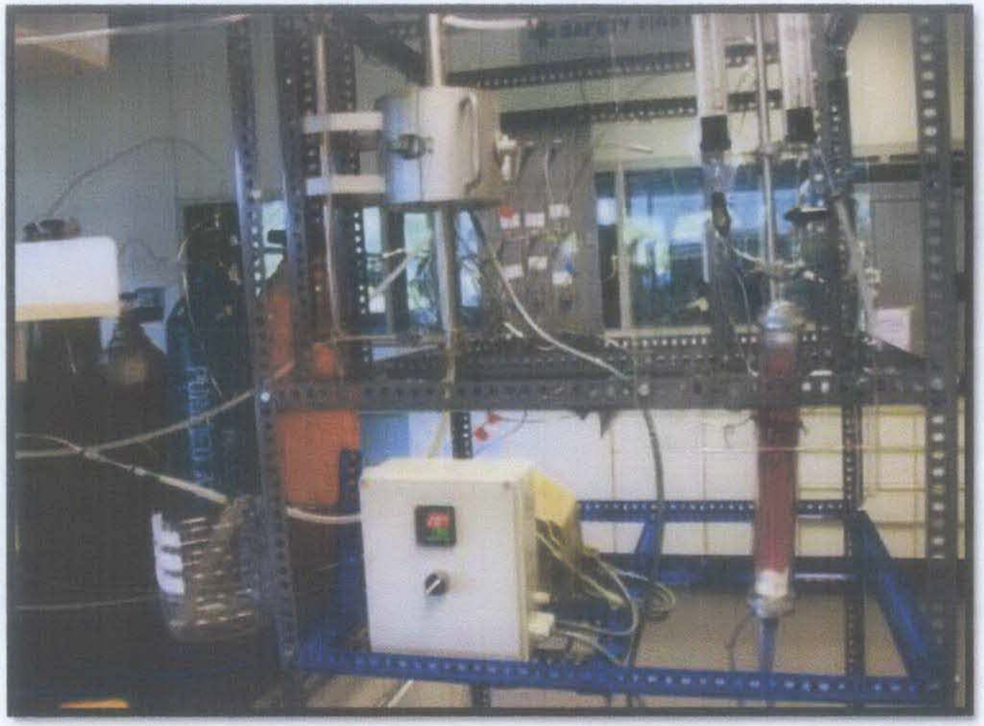

Figure 14: Real Reactor